Section 3

THE INTERNAL COMBUSTION ENGINE

Quick Reference Data

In a spark-ignition (SI) engine, the fuel/air mixture is compressed to a pressure and corresponding temperature (400°-600°C) generally below its auto-ignition threshold, with the mixture being ignited by a spark shortly before the piston reaches top-dead-center.

In a compression-ignition (CI) engine, air is compressed to a sufficiently high temperature (700°-900°C) to cause auto-ignition of fuel upon injection into the cylinder shortly before the end of the compression stroke.

Principal Design Parameters for an SI Engine

- **Compression Ratio (CR):** increasing CR increases fuel economy with two drawbacks: increased tendency to knock and higher NO_x emissions.

- **Combustion Chamber Design:** recent research has focused on faster burning designs, i.e., compact chamber, centrally located spark plug, high turbulence swirl induction, and four/five valves per cylinder.

- **Valve Timing:** the opening and closing of the intake and exhaust valves for the exchange of gases in the cylinders of a four-stroke, internal combustion engine. Ideally, a larger valve overlap (a very short time in which both the intake and exhaust valves are slightly open) is needed at high speeds for performance, and a smaller overlap is needed at idle and slow engine speeds to lower emissions.

- **Fuel Management:** sequential port fuel injection has shown favorable results over carburetion when used in an alcohol-burning engine (especially for methanol) because the mean effective pressure and thermal efficiency improve significantly over most of the operating range.

The Key Operating Parameters for SI Engines

- **Equivalence Ratio:**

    -- At lower equivalence ratios (lean burn conditions), engines operate more efficiently.

    -- Lean burn conditions, while providing better thermal efficiency and lower hydrocarbon (HC) and CO emissions, produce higher NO_x emissions.

- **Spark Advance:** optimum spark setting will depend on rate of flame development and propagation and the length of the flame path across the combustion chamber.

  -- As the spark is advanced, HC emissions increase up to the lean misfire limit.

  -- As the timing is advanced, combustion temperature is increased and NO_x formation increases.

  -- The influence of ignition timing on fuel consumption is opposite to the influence it exerts on pollutant emissions.

- **Exhaust Gas Recirculation (EGR):**

  -- Increasing amount of EGR decreases NO_x emissions, but increases HC emissions and fuel consumption.

  -- Increasing amount of EGR requires advancing the spark timing as the equivalence ratio decreases.

Key Design Parameters for Alcohol Combustion

- Higher octane
- Greater enthalpy of formation
- Lower flame temperature
- Extended lean limit of operation

Useful Terms and Definitions (also see Glossary)

- **Adiabatic:** occurring without loss or gain of heat.

- **Compression Ratio (CR):** the maximum cylinder volume divided by the minimum cylinder volume.

- **Enthalpy Requirement:** the additional heat input required by the engine's fuel induction system to achieve the required degree of fuel vaporization for smooth operation.

- **Equivalence Ratio:** measure of the actual fuel/air mixture to the stoichiometric fuel/air ratio.

- **Exhaust Gas Recirculation (EGR):** the recirculation of exhaust gases to the combustion chamber to reduce the peak combustion temperature for the reduction of NO_x emissions.

- **Maximum Brake Torque (MBT):** the timing associated with a particular fuel for a particular combustion chamber; aside from the fuel/air mixture, the moment of ignition has the greatest influence on pollutant emissions.

- **Octane:** identifies the ability of a fuel to resist spontaneous combustion or pre-ignition; the higher the octane the less likely that a fuel will prematurely ignite (knock).

- **Spark Advance:** the optimal spark setting, an operating parameter dependent on the rate of flame development and propagation within the combustion chamber.

- **Stoichiometry** (of fuel/air): the proportion required between fuel and air for a specific fuel to allow complete combustion of the chemical reactions to occur (i.e., the proportions that are exactly right).

Key Issues and Implications

Issues and Implications

*Issue #1:   Optimization of Spark Ignition Engines for
                    Alcohol Fuels by Increasing Compression Ratios
                    (CRs).*

**Increasing the compression ratio increases fuel economy by
improving thermal efficiency. Because of their higher octane
ratings and lean burn characteristics, alcohol fuels allow the
use of higher CR.**

*Implications of Higher Compression Ratios (Regardless of Fuel
Used):*

- Higher fuel economy

- Increased tendency to knock

- Higher temperature in the combustion chamber,
  resulting in lower HC and CO emissions and higher
  NO_x formation.

Proposed Solutions:

- By increasing the volumetric content of alcohol in
  gasoline, an engine can operate at higher CRs without
  knock. Dedicated alcohol engines have been found
  to operate smoothly at CRs of up to 12.5 - 13.5, while
  production gasoline engines are limited to CRs of 8-
  12.

- Alcohols have inherently lower flame temperatures
  than gasoline and, under lean burn conditions, tend
  to produce less NO_x.

Detailed Information: Refer to pages 3-3 and 3-4.

Issue #2:   *The Opportunities for Optimized Engine/Vehicle Design Provided by the Inherent Characteristics of Alcohol Fuels*

Alcohol fuels have a number of characteristics which can improve the performance of internal combustion engines. Relative to gasoline, methanol and ethanol have higher octane ratings, greater heat of vaporization, and lower flame temperatures. They have also been shown to possess an extended lean limit of operation.

Implications of Unique Characteristics of Alcohol Fuels:

- The use of alcohol fuels in production vehicles designed for gasoline will not take full advantage of the beneficial characteristics of those fuels.

- A flexible fuel vehicle (FFV), by definition, must be designed as a compromise between the characteristics of gasoline and alcohol, and may not optimize the use of either fuel.

Proposed Solutions:

- To achieve the maximum benefits from alcohol fuels -- increased fuel efficiency, increased power, and reduced emissions -- the vehicles and vehicle engines should be redesigned to operate on neat alcohol fuels or high alcohol/gasoline blends.

- FFVs should be considered, at best, as a temporary bridge to dedicated fuel vehicles.

Detailed Information: Refer to pages 3-17 and 3-18.

Section 3
THE INTERNAL COMBUSTION ENGINE

- Engine Design
- Operating Parameters
- Key Design Parameters for Alcohol Combustion

Introduction

Internal combustion engines can be characterized by two primary design features: method of ignition and type of operating cycle. The method of ignition -- spark ignition or compression ignition -- dictates a host of other characteristics including the type of fuel used, the method of preparing the fuel/air mixture, the design of the combustion chamber and the combustion process, as well as load control, engine emissions and operating characteristics.

Recent alcohol fuel research conducted with particular engine types has varied considerably. Most research in the past five years has been conducted on four-stroke, spark-ignition engines operating on methanol blends, although considerable work has also been done on methanol-powered modified diesel prototypes to power mass transit buses because of reduced soot and particulate formation. [1] Work on test-bench, two-stroke spark ignition engines using methanol fuel has shown abnormal combustion (knock) characteristics even at low compression ratios and loads. [2]

The following discussion will focus on the operating characteristics of spark-ignited, four-stroke engines using alcohol fuels. These engines are the standard production engines used in passenger cars in the United States, and variations of these engines have been successfully used in Brazil for alcohol blends and neat fuels. Also, Compression Ignition (CI) or diesel engines cannot use alcohol fuels without ignition improvers or engine modifications, such as the addition of glow plugs, to assist combustion. Due to the limited amount of recent engine research available with ethanol, the data will focus on the use of methanol; however, because of the similarities between the two alcohol fuels, much of the research findings may also apply to ethanol.

3-1

Engine Design

In a spark-ignition (SI) engine, the fuel/air mixture is compressed to a pressure and corresponding temperature (400°-600°C) generally below its auto-ignition threshold. The mixture is then ignited by a spark shortly before the piston reaches top-dead-center (TDC). In a compression-ignition (CI) engine, air is compressed to a sufficiently high temperature (700°-900°C) to cause auto-ignition of the fuel upon injection into the cylinder shortly before the end of the compression stroke. [3] Fuels that are routinely used in SI engines generally have higher octane ratings* (see Section 2), while those used for CI engines have higher cetane ratings.**

Most internal combustion engines operate on the four-stroke cycle: each cylinder requires four strokes of its piston or two revolutions of the crankshaft to complete the sequence of events required to produce one power stroke. To obtain a higher power output from a given engine size, the two-stroke engine was developed. Each cylinder requires only two strokes of its piston or one revolution of the crankshaft to complete one power stroke. [4]

Automotive engine design requires tradeoffs between performance, emissions, and efficiency. Complete combustion is a theoretical concept that explains what *should* occur within the combustion chamber of an engine. Ideally, the products of that combustion process are carbon dioxide, water vapor, and nitrogen. Unfortunately, our inability to control combustion reaction rates over the wide ranges at which engines operate results in incomplete combustion and the formation of a broad range of pollutants. Since the mid-70s, catalytic converters have been employed in the United States to reduce the formation of pollutants by allowing combustion reactions to reach completion.

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*A number that is used to measure the antiknocking properties of a liquid motor fuel.

**A measure of the ignition value of a diesel fuel.

The principal design parameters for a spark-ignition engine --
whether fueled by alcohol, alcohol-gasoline blends, or gasoline --
are compression ratio (CR), combustion chamber design, valve
timing, and fuel management.

Compression Ratio

Compression ratio (CR) is defined as the maximum cylinder volume
(when the piston is at the bottom of its reciprocating path) divided
by the minimum cylinder volume (when the piston is at Top Dead
Center or TDC). Increasing the compression ratio is a known
method of increasing fuel economy by improving thermal efficiency.
Because of their higher octane ratings, alcohol fuels allow the use
of higher compression ratios. However, the introduction of high
compression ratios has two potential drawbacks: an increased
tendency to knock and higher NO_x emissions. [5] Alcohol blends
can help solve the problem of knock at elevated compression ratios.
Using a variable-compression ratio, single-cylinder engine, the effect
of methanol content on the knock-limited compression ratio
(KLCR) is shown below in Figure 3-1. [6]
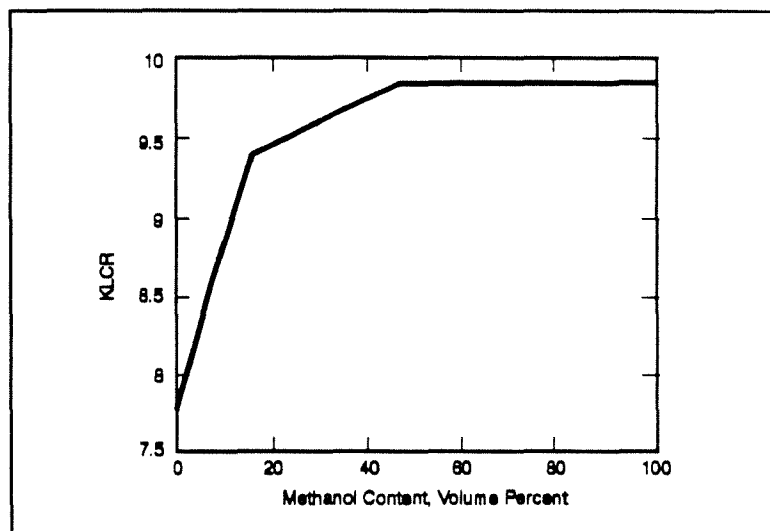
Figure 3-1., The effect of methanol content on Knock
Limited Compression Ratio (KLCR).

Policy Issue #1

> Because of their higher octane ratings and lean burn characteristics, alcohol fuels allow the use of higher compression ratios.

As the volumetric content of ethanol or methanol in the gasoline blend is increased, the engine can operate at higher CRs without knock. [7] Current gasoline passenger automobile engines produced in the United States have CRs ranging from 8-12 with race engines limited to 14. Dedicated alcohol engines have been found to operate smoothly at CRs up to 12.5-13.5 [8,9], although alcohol-fueled racing engines have been shown to withstand CRs up to 18. [10] As the CR is increased, the temperature in the combustion chamber increases, resulting in increased NO_x formation. However, as shown in Figure 3-2 [11], methanol has inherently lower flame temperatures than gasoline, and therefore tends to produce less NO_x.
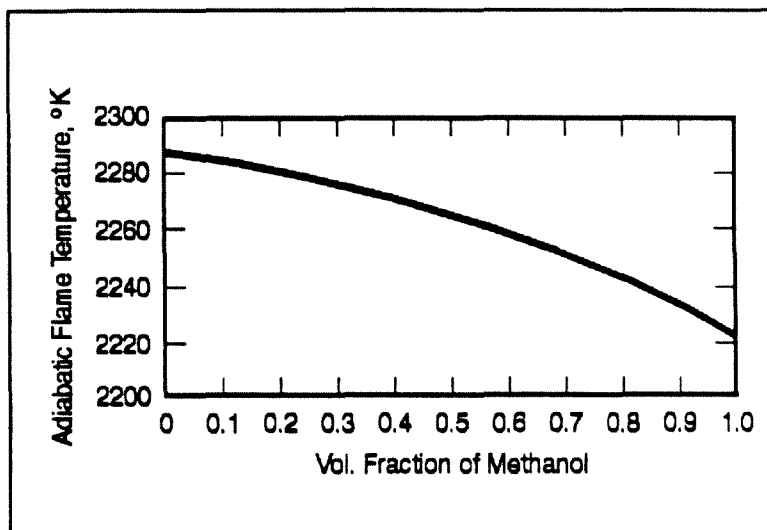
Figure 3-2., Adiabatic flame temperatures of indolene-methanol blends.

Combustion Chamber Design

Alcohol fuels, alcohol/gasoline blends, and gasoline can be burned in the same SI engine designs. There has been continuing debate among researchers over the optimum SI engine combustion chamber design for alcohol fuels. Recent innovations have focused on faster burning designs -- i.e., compact chambers, centrally located spark plugs, high turbulence swirl induction, and four and five valves per cylinder. A faster burning chamber with its shorter burn time permits operation with more excess air or leaner mixtures, and provides a more repeatable combustion pattern, thus providing lower cycle-by-cycle variability over the entire operating range. [12] A four or five valve per cylinder engine reveals flow areas quicker than a two valve for cylinder engine. Two or three valves have more perimeter than a single large one of equal area, and flow at low lift is proportional to perimeter. The influence of spark-plug position and 4-valve designs on fuel consumption and hydrocarbon (HC) emissions is shown in Figure 3-3. [13]
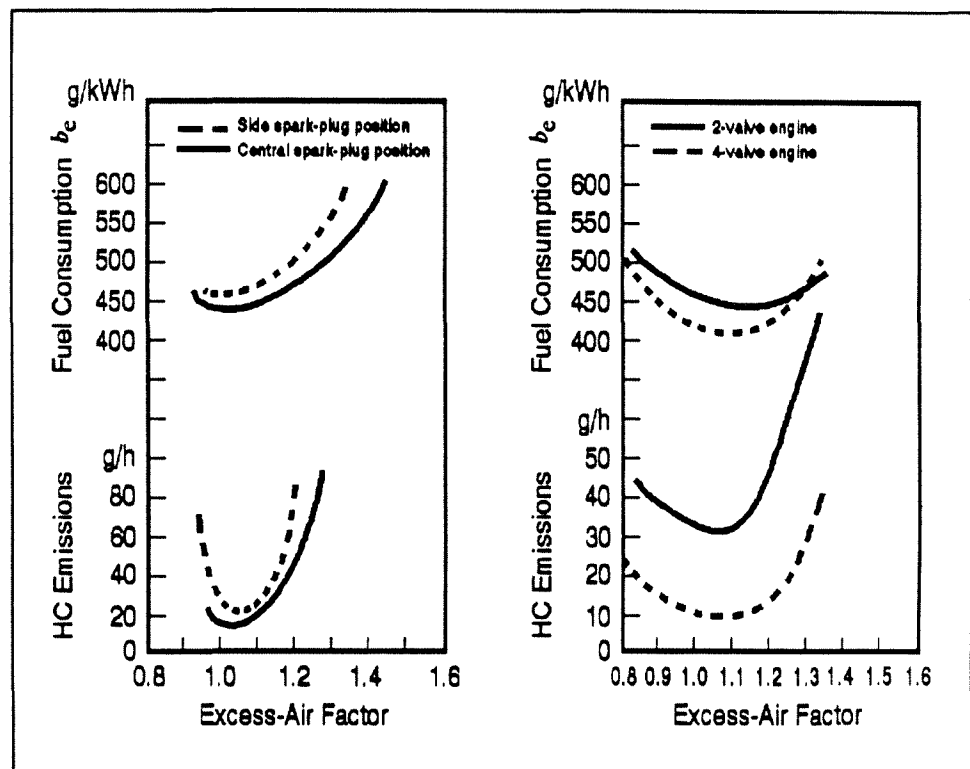
Figure 3-3., Influence of spark-plug location and valve configuration on fuel consumption and HC emissions.

Because of their ability to create more turbulence, compact chamber designs reduce the octane requirements of the fuel, therefore allowing higher compression ratios to be used resulting in lower unburned HCs and increased thermal efficiency. Because methanol has a faster burning velocity than gasoline as well as operating efficiently at higher compression ratios, it shortens the burn time and extends the stable operating limit regardless of combustion chamber geometry. Figure 3-4 [14] compares the faster laminar burning velocity of methanol to indolene, a common test reference gasoline.
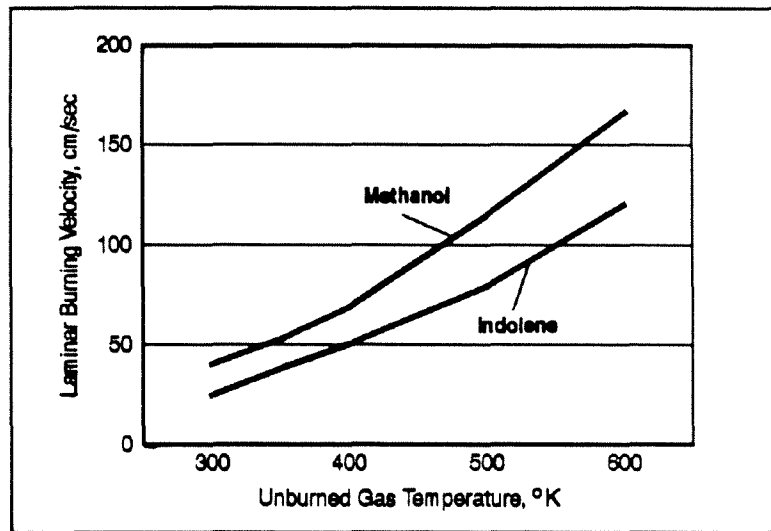
Figure 3-4., Experimental laminar burning velocities for methanol/ and indolene/air mixtures.

Valve Timing

The exchange of burned gas in the cylinder for fresh mixture occurs through the alternate opening and closing of the inlet and exhaust valves. The effect of changing an engine's valve timing for optimizing performance with alcohol fuels has not been thoroughly researched. The camshaft dictates the valve timing, i.e., the timing of opening and closing the valves in relation to each other. There is a short period of time near the beginning of the intake stroke in which the intake and exhaust valves are both slightly open called overlap, during which the residual gas content is determined. The

residual gas content is the burned gas remaining in the cylinder that is not expelled while the exhaust valve is open. The amount of residual gas content has a direct effect on efficiency and the level of HC emissions. The residual gas content along with the exhaust gas recirculation (EGR) (used to control NO_x), effectively determine the stable operating limit of a particular engine. [15] The use of methanol allows greater tolerance to EGR and extends the stable operating limit of the engine. [16,17] Camshaft modifications to flatten the torque curve for methanol optimization have resulted in decreases in fuel economy. [18] On most cars, the valve timing is optimized for one engine speed, causing the rate of formation of HC pollutants and the volumetric efficiency to vary with engine speed. However, both Acura and Nissan [19] have produced cars with engines that incorporate variable valve timing. Although the two approaches are substantially different, the effects are the same: a large valve overlap at high engine speeds for power and a small overlap at low engine speeds for lower unburned hydrocarbon emissions, smoother idle, and improved fuel economy. For further information on valve timing research, refer to [20,21].

Fuel Management

Sequential port fuel injection has demonstrated superior fuel management characteristics versus carburetion when used on an alcohol-burning engine. This is true for both methanol and ethanol. As shown in Figure 3-5 [22], the mean effective pressure and the thermal efficiency improve significantly over most of the operating range. The higher constant thermal efficiency observed is typical of fuel injections' ability to extend maximum efficiency through a greater portion of the operating range.

The behavior exhibited above is typical of gasoline engines as well. However, because of methanol's much lower heating value it requires much higher mass flow rates for a stoichiometric air/fuel mixture than does gasoline. Due to the increased fluid flow through the intake manifold, more liquid methanol forms films on the intake manifold walls causing worse mal-distribution problems than are encountered with gasoline. [23] Ethanol's heating value
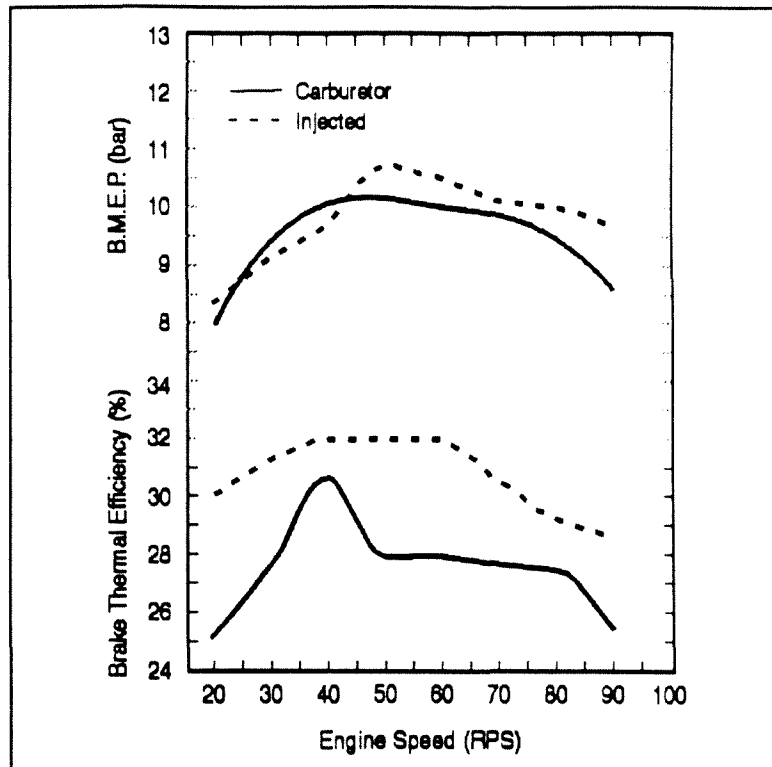
Figure 3-5., Comparison between carburetor and sequential fuel injection.

lies between that of methanol and gasoline. Because the use of ethanol requires less of a fuel flow increase than methanol, the positive effect of port fuel injection is thought to be greater for methanol than ethanol. The higher thermal efficiency for fuel injection shown above in Figure 3-5 [24] is attributed to better fuel distribution between cylinders.

Operating Parameters

The operating parameters for a SI engine vary according to its specific design and are very closely related to one another. Compromises exist between design goals and it becomes necessary to optimize accordingly. Some engines have been designed using lean-burn strategies to minimize HC and CO emissions while

reducing fuel consumption while others are built strictly for performance. Catalytic after-treatment of exhaust is vital to ensure that emissions are kept to an absolute minimum. Because of the key role played by the catalytic converter in engine emission clean-up, it becomes necessary to separate emissions into two categories: "engine out" emissions and tailpipe emissions (after the catalyst). The key operating parameters are **equivalence ratio, spark advance** and **exhaust gas recirculation.** It is important to realize that the parameters are closely interrelated. Performance of a particular parameter can be compared by examining their effects on the specific fuel consumption, thermal efficiency, and torque.

Equivalence Ratio

The equivalence ratio (ϕ) is a measure of the actual fuel/air mixture $(F/A)_{actual}$ to the stoichiometric fuel/air ratio $(F/A)_s$. **Stoichiometry** is the proportion required between fuel and air for a specific fuel to allow complete combustion of the chemical reactions to occur. The excess air ratio is also used and is inverse of the equivalence ratio (ϕ^{-1}). Its purpose is to describe whether the engine is operating on a lean or rich fuel/air mixture. Both are defined below: [25]

$$\text{Equivalence Ratio} \quad \phi = \frac{(F/A)_{actual}}{(F/A)_s}$$

For fuel-lean mixtures: $\phi < 1, \lambda > 1$

For stoichiometric mixtures: $\phi = \lambda = 1$

$$\text{Excess Air Ratio} \quad \lambda = \phi^{-1} = \frac{(A/F)_{actual}}{(A/F)_s}$$

For fuel-rich mixtures: $\phi > 1, \lambda < 1$

At lower equivalence ratios or lean burn conditions, engines operate more efficiently. Because of their oxygenated composition, alcohol fuels and alcohol-based ethers allow the use of leaner equivalence ratios. Figure 3-6 [26] shows the relation between equivalence ratio and thermal efficiency for methanol and gasoline.

The maximum efficiency attainable by a lean mixture of gasoline
(27%) can be attained with rich mixtures of methanol. Work
conducted on a test engine operating on ethanol produced similar
results. [27] Because the efficiency values are measured at the
fuel's knock limited compression ratio (KLCR), the second figure
is included to discriminate between the effect of the fuel and the
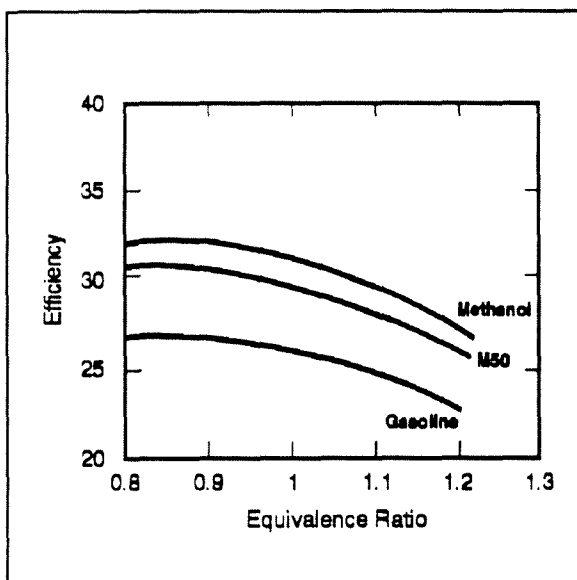effect of KLCR on efficiency.

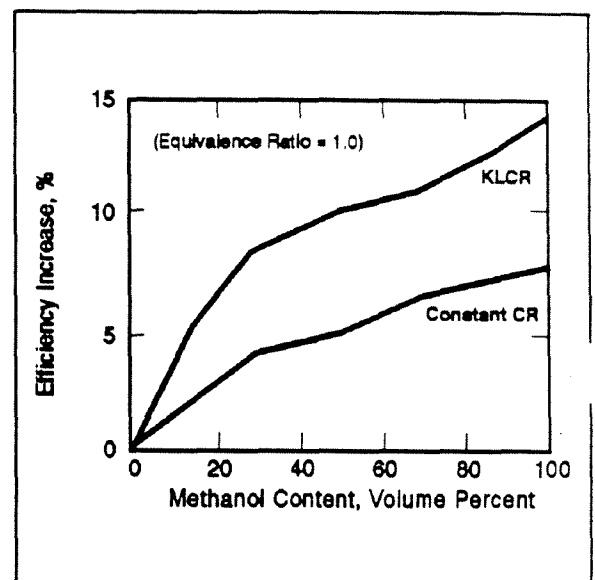
Figure 3-6-1., The effect of equivalence ratio and methanol content on brake efficiency.

Figure 3-6-2., A comparison of efficiency increases due to methanol content at KLCR and constant CR.

Figure 3-7-1 [28] shows the relation between equivalence ratio and
power for methanol and gasoline. The peak power achieved with
gasoline was attained by the fuels containing methanol at much
leaner conditions. Again, because an increase in compression ratio
is accompanied by an increase in power, the right hand illustration
in Figure 3-7-2 [29] shows the contribution of the compression ratio
vs. the methanol fuel content.
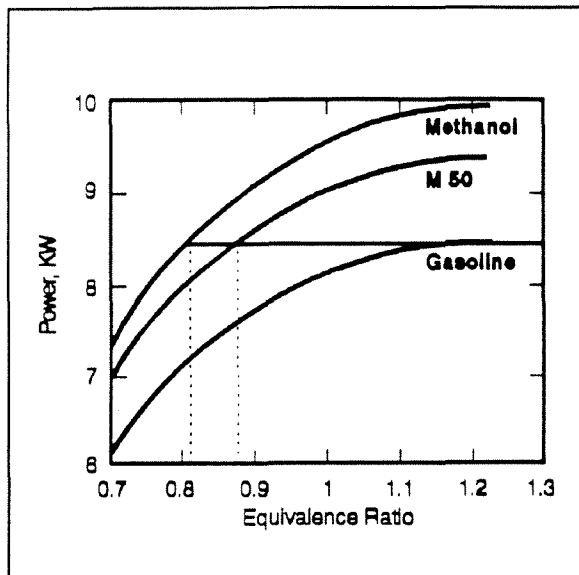
Figure 3-7-1., The effect of equivalence ratio and methanol content on power output.
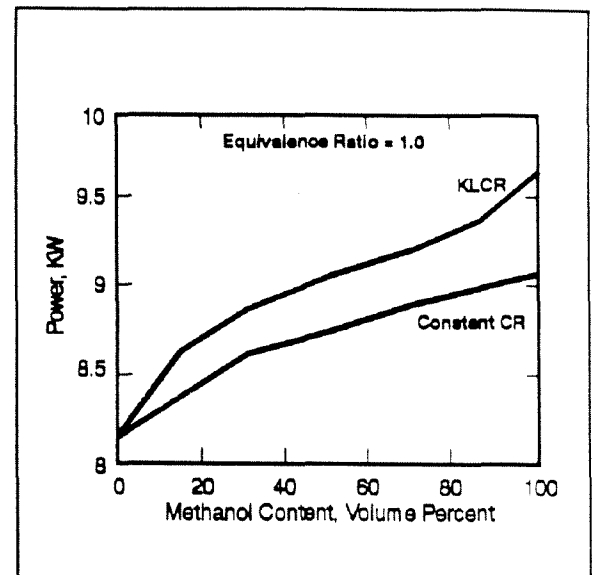
Figure 3-7-2., A comparison of power output due to methanol content at KLCR and constant CR.

One of the issues in modern engine design is the control of specific pollutants. Increasing the percentage of methanol and lowering the equivalence ratio decreases hydrocarbon and CO emissions but increases the creation of NO_x and formaldehyde, as can be seen in Figure 3-8. [30]

Lean burn strategies, while providing better thermal efficiency and lower hydrocarbon and CO emissions, produce higher NO_x emissions. Work conducted at Toyota has shown that using high swirl induction and lean burn with EGR to control NO_x is possible, at the expense of driveability. The Toyota researchers agree that additional experimentation is needed before these technologies are production-ready. [31]
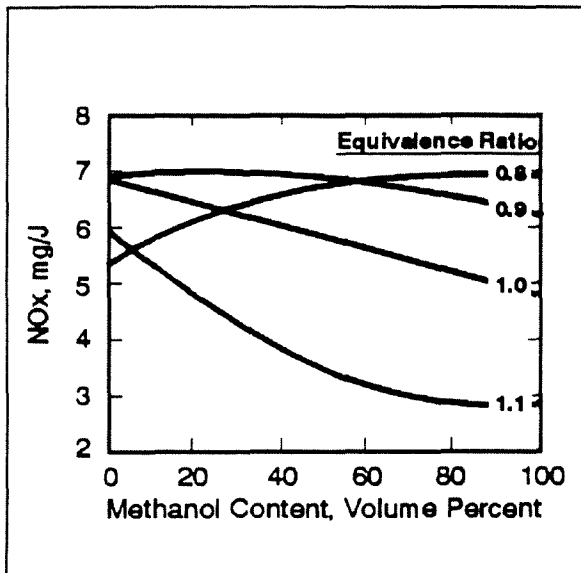
Figure 3-8-1., The effect of methanol content and equivalence ratio on NO_x emissions.
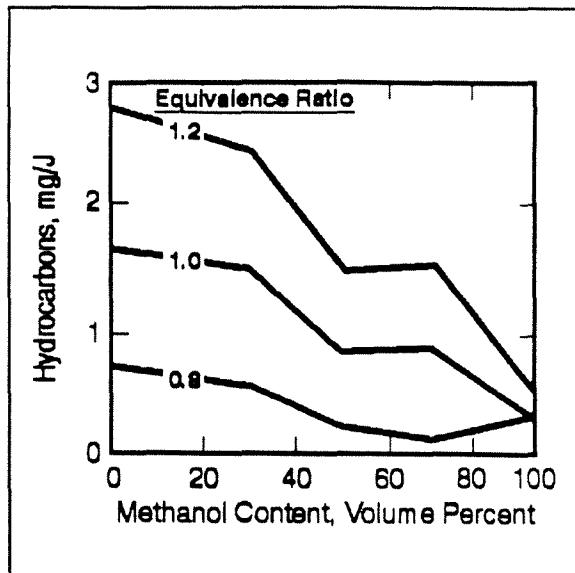
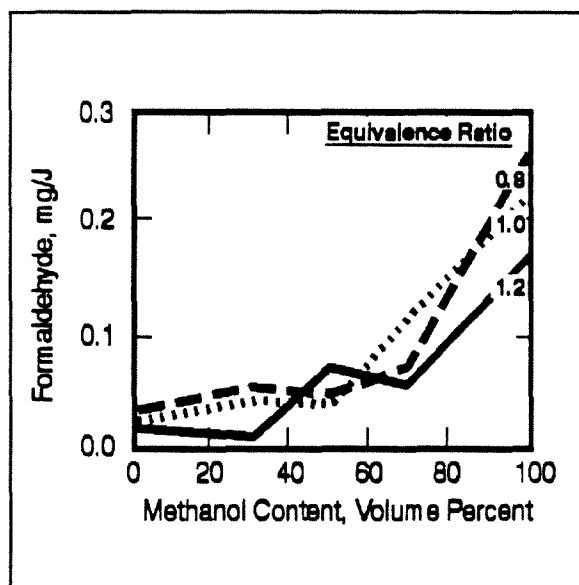Figure 3-8-2., The effect of methanol content and equivalence ratio on HC emissions.

Figure 3-8-3., The effect of methanol content and equivalence ratio on formaldehyde emissions.

Spark Advance

The spark plug is fired before the piston reaches top dead center (TDC) on its compression stroke. The ignition point is presented as the "spark advance," in degrees of rotation of the crank shaft before TDC. Because of the time required for the flame development (combustion) process to build pressure in the cylinder, there is a maximum brake torque (MBT) timing associated with a particular fuel for a particular combustion chamber. [32] The optimum spark setting will depend on the rate of flame development and propagation and the length of the flame travel path across the combustion chamber. The use of both ethanol and methanol has shown to decrease the spark advance required for MBT. [33,34] As shown in Figure 3-9 [35] for methanol, as the percentage of alcohol increases in the gasoline/alcohol mixture, less spark advance is required and the MBT timing shifts toward Top Dead Center or TDC. This is an indication of methanol's higher burning velocity. In the drawing, DBTDC signifies Degrees Before Top Dead Center.
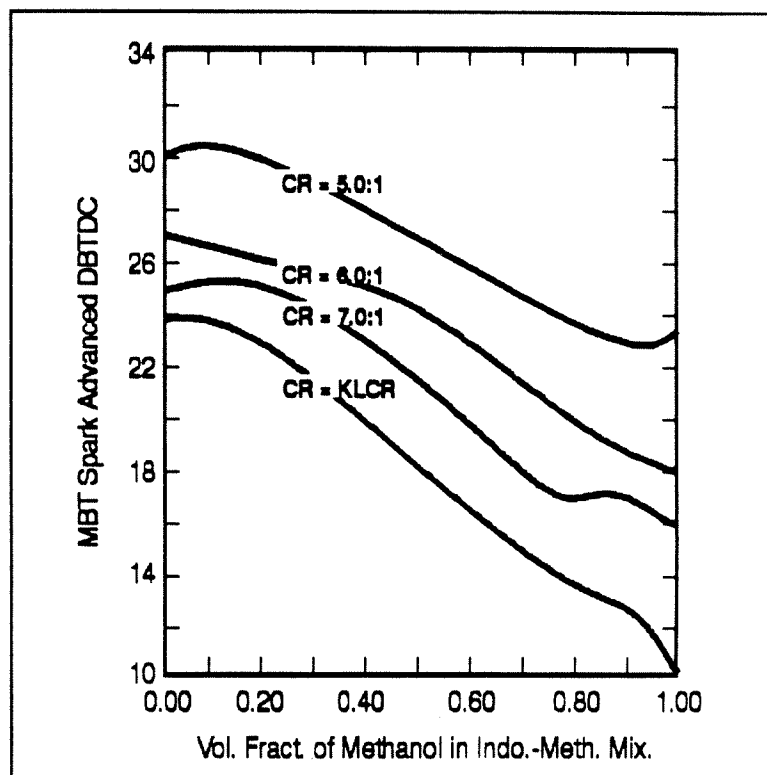

Figure 3-9., The effect of methanol content on MBT spark timing at different compression ratios.

The importance of proper ignition timing cannot be overemphasized. Aside from the fuel/air mixture, the moment of ignition has the greatest influence on pollutant emissions. As shown below in the set of drawings in Figure 3-10 [36], both HC and NO_x emissions are much higher at 50° before TDC than at 20°, for the range of equivalence ratios from 0.75 to 1.2. As the spark is advanced (away from TDC), HC emissions increase up to the lean misfire limit. As the timing is advanced, the combustion temperature is increased and NO_x formation increases. CO emissions are almost completely independent of ignition timing and are primarily a function of the fuel/air ratio.
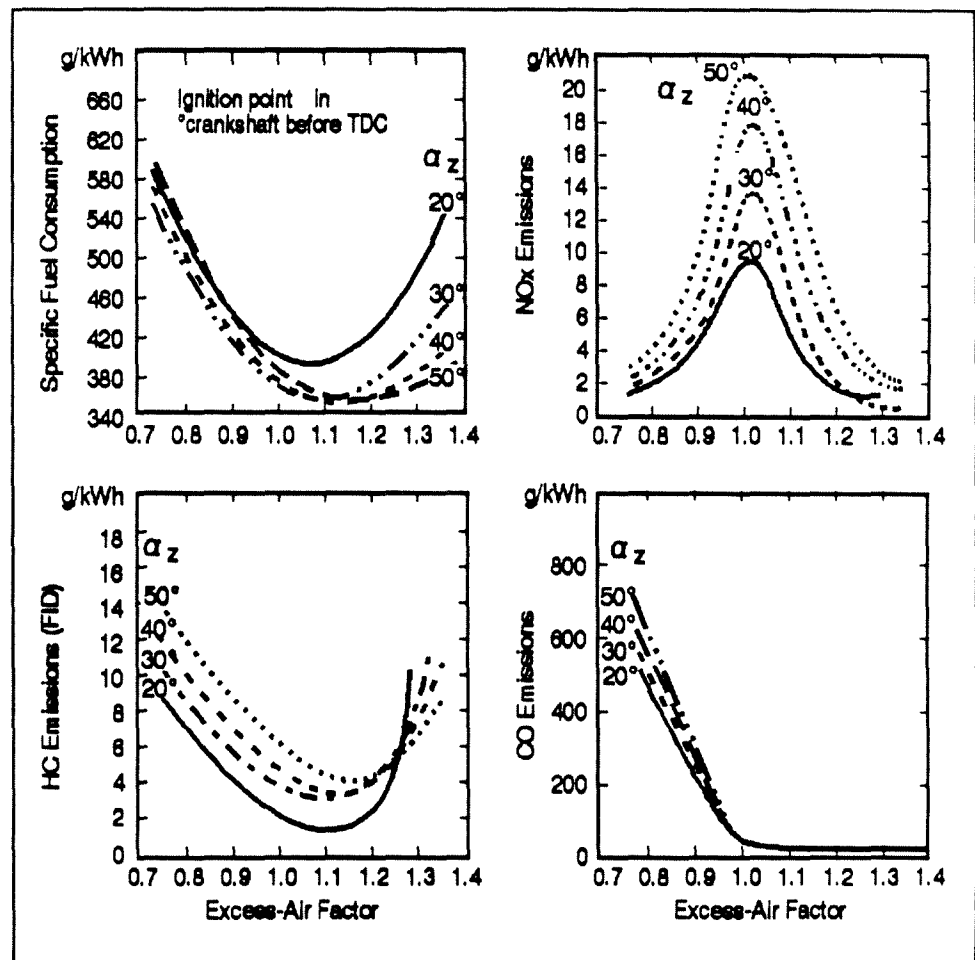
Figure 3-10., The influence of excess air ratio and ignition timing on pollutant emissions and fuel consumption.

The influence of ignition timing on fuel consumption is opposite to the influence it exerts on pollutant emissions. As the timing is advanced, specific fuel consumption goes down. At lean excess air ratios, the spark advance can be set for either high fuel efficiency or low emissions.

Exhaust Gas Recirculation (EGR)

EGR refers to the recirculation of exhaust gases to the combustion chamber to reduce the peak combustion temperature for the reduction of NO_x emissions. The lower flame temperature of alcohols produce less NO_x, reducing the EGR required for NO_x control. Because methanol is a faster burning fuel, its tolerance to EGR was theoretically found to be higher. [37,38] However, the reduction capabilities of NO_x with methanol were also found to be higher than gasoline. An actual prototype engine test revealed that 40% less EGR rate was needed with M-85 (85% methanol plus 15% gasoline) to achieve the same NO_x reduction as gasoline. [39] The maximum EGR rate in a gasoline or gasoline/alcohol fuel engine is limited by the increase in HC emissions that can be tolerated as well as the maximum burned gas fraction before stable combustion is lost.

The effect on specific fuel consumption (SFC) for a gasoline-powered engine varies with the excess air factor and EGR rate as shown in Figure 3-11. [40] Richer mixtures with higher EGR rates result in a higher SFC (i.e., poorer fuel economy).

Prototype engine work has revealed that engines operating on methanol behave similarly to the gasoline engines depicted in Figure 3-11. It is important to note that increasing EGR requires advancing the spark ignition as the equivalence ratio decreases, as shown in Figure 3-12. [41]
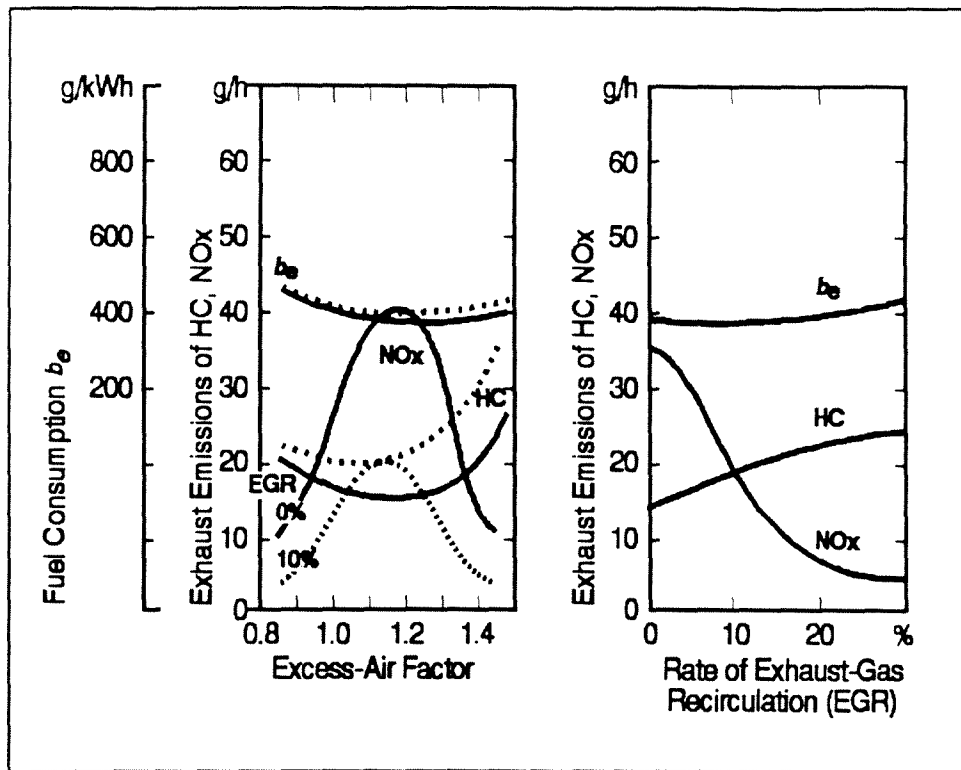
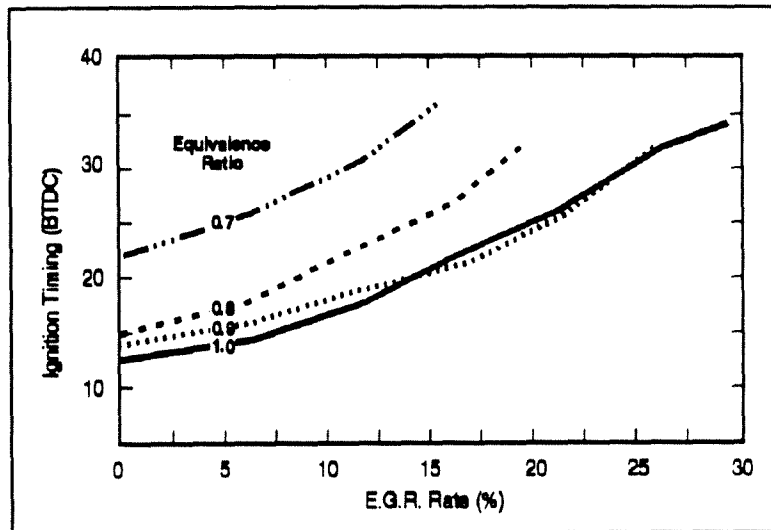Figure 3-11., The influence of Exhaust-Gas-Recirculation (EGR) on pollutant formation and fuel consumption.

Figure 3-12., The effect of increasing EGR on ignition timing and equivalence ratio for a methanol fueled engine.

Key Design Parameters for Alcohol Combustion

Policy Issue #2

> Relative to gasoline, methanol and ethanol have higher octane, greater heat of vaporization, and lower flame temperatures. They have also been shown to exhibit an extended lean limit of operation.

By exploiting these characteristics, a methanol-fueled engine can operate at leaner fuel/air ratios than those burning gasoline to improve thermal efficiency and reduce the concentrations of both regulated and unregulated exhaust gas emissions. [42]   A high compression, lean burn stratified charge engine may be the goal for designing an optimized methanol engine.

Stratified charge implies a heterogeneous fuel/air mixture distribution in the combustion chamber. Combustion is initiated in the fuel rich zone and spreads to the more lean regions. Stratified engines are very fuel efficient but due to the difficulty encountered in regulating the fuel/air mixture with today's oxygen sensors and three-way catalysts, research on this technology has been reduced. [43] Ricardo developed and tested a high compression ratio compact chamber engine with optimization for methanol. Employing a CR of 13:1 with lean burn strategy, fuel efficiency improvements of 10% were noted. For more detailed information, refer to [44].

Methanol's high heat of vaporization provides a lower intake temperature to the engine. A significant amount of heat is removed from the incoming air to vaporize the liquid methanol fuel. This cooling effect increases the charge density in the cylinder (since cooler gases are more dense than warmer gases), improving volumetric efficiency and increasing power. Unfortunately, this characteristic also is responsible for the difficulty associated with cold-starting methanol vehicles (see Section 6). In methanol

combustion, the ratio of moles-of-product to moles-of-reactant are 1.209 times that of gasoline. [45] This results in higher cylinder pressure, which in turn results in a higher power output. These advantages are realized without significant alterations to the engine for methanol optimization. Using flexible fuel technology, Ford measured a 3% improvement in fuel efficiency on M-85 and a 5-7% increase in power over gasoline operation. Because flexible fuel vehicles are designed to operate on gasoline as well as methanol, they cannot be optimized to take full advantage of methanol's properties. Ethanol's heat of vaporization is slightly less than methanol's. Similar increases in efficiency and cold start problems occur when operating on ethanol.

Clearly, certain negative effects of methanol combustion exist that will have to be further researched before dedicated vehicles are mass-produced. While the combustion of methanol releases less hydrocarbons than gasoline, it is still uncertain what effect unburned methanol emissions have on air quality. Figure 3-13 [46] shows that formaldehyde levels have been found to be significantly higher than gasoline.
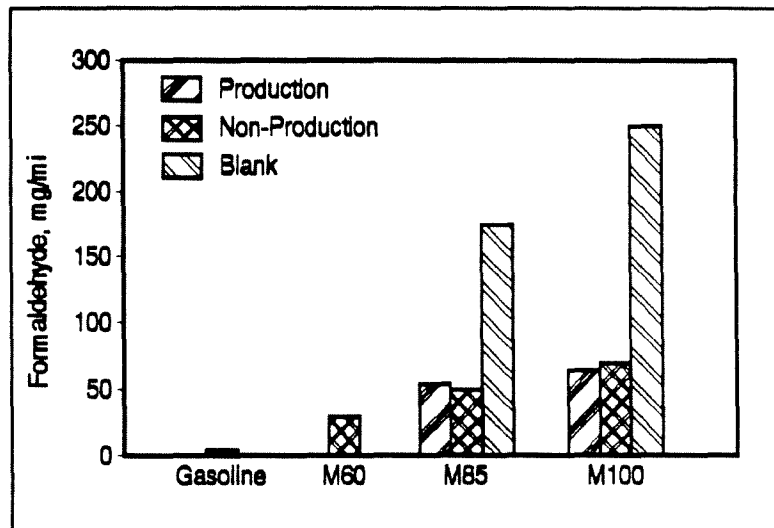

Figure 3-13., Comparison of formaldehyde emissions from production and non-production catalysts aged to 50K miles.

Greatly increased engine wear at cold temperatures has been observed with methanol as a fuel (when compared to gasoline, ethanol, and ethanol/water mixtures), and this is multiplied when water is added to the methanol fuel as shown in Figure 3-14 [47] below. For further information refer to [48].
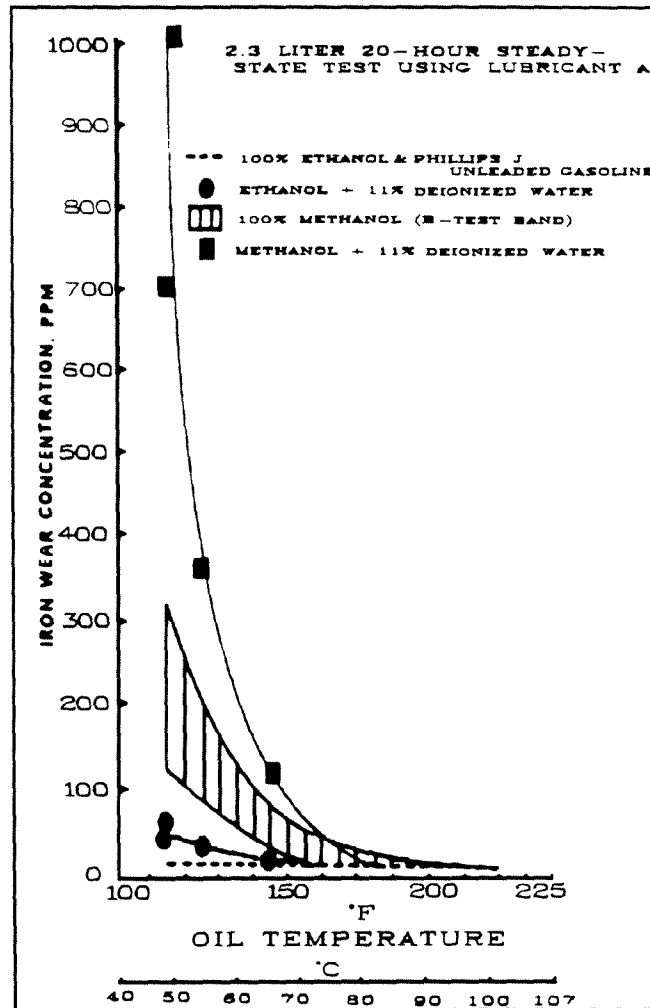

Figure 3-14., Effect of oil temperature on engine iron wear with various fuels.

ENDNOTES:

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4. Heywood, John B., *Internal Combustion Engine Fundamentals* (New York: Mcgraw-Hill Inc., 1988), p. 11.

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7. Patel, K.S., and N.A. Henein, "Effect of Blending Methanol and Indolene on the Burning Velocity and Performance in a CFR-S.I. Engine," SAE Paper 860235, 1986.

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